The NTF Inlet Guide Vanes Thermal Gradient Problem and Its Mitigation

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Abstract

The National Transonic Facility (NTF) utilizes Inlet Guide Vanes (IGV) to provide precise, quick response Mach number control for the tunnel. During cryogenic operations, the massive IGV structure can experience large thermal gradients, measured as "Delta T or ΔT", between the IGV ring and its support structure called the transfer case. If these temperature gradients are too large, the IGV structure can be stressed beyond its safety limit and cease operation. In recent years, ΔT readings exceeding the prescribed safety limits were observed frequently during cryogenic operations, particularly during model access. The tactical operation methods of the tunnel to minimize ΔT did not always succeed. One obvious option to remedy this condition is to warm up the IGV structure by disabling the main drive operation, but this "natural" warm up method can takes days in some cases, resulting in productivity loss. This paper documents the thermal gradient problem associated with the IGV structure during cryogenic operation and how the facility has recently achieved an acceptable mitigation which has resulted in improved efficiency of operations.

Nomenclature

bar	=	100KPa
°C	=	Degrees Celsius
CAD	=	Computer Aided Design
cm	=	Centimeter
δ	=	IGV Blade Angle
Delta T, ΔT	=	Temperature Difference
2-D	=	Two Dimensional
F	=	Fan Pressure Ratio
°F	=	Degrees Fahrenheit
FAS	=	Facility Automation System
FEA	=	Finite Element Analysis
ft, ft^2	=	feet, square feet
gpm	=	Gallons Per Minute
Hp	=	Horsepower
Hrs	=	Hours
IGV	=	Inlet Guide Vanes
in, in^2	=	Inch, Square inches
K	=	thousand
Kg	=	Kilogram
KPa, Pa	=	Kilo Pascal, Pascal
KW	=	Kilowatt
LaRC	=	Langley Research Center
Lbs	=	pounds
lbs-in	=	pounds-inch
lbs/sec	=	pounds per second
LN2	=	Liquid Nitrogen
lpm	=	Liters per minute
m	=	Meter
mm	=	Millimeter
M	=	million
MW	=	Megawatt
N	=	Newton
NASA	=	National Aeronautics & Space Administration
N2	=	Gaseous Nitrogen
NTF	=	National Transonic Facility
PLC	=	Programmable Logic Controller
PSF, psf	=	pounds per square foot
PSI, psi	=	pounds per square inch
Psia, Psig	=	Pounds per square inch absolute, gage
Psia, Psid	=	Pounds per square inch absolute, differential
RPM	=	Revolutions per Minute
s, sec	=	second(s)
SMSS	=	Sidewall Model Support System
TExxxx	=	Thermocouple xxxx
U	=	Fan Blade Speed
UOH	=	User Occupancy Hours

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Introduction

The National Transonic Facility (NTF) is a fan-driven, closed-circuit, continuous-flow cryogenic pressurized wind tunnel that became operational in 1984 (Figure 1). The facility has the capability to adjust test conditions to match model size and has independent control of total temperature, pressure, and fan speed to allow isolation and study of pure compressibility (Mach) effects, viscous (Reynolds number) effects, and aero-elastic (dynamic pressure) effects. Combinations of these test parameters can yield Reynolds numbers from 2 to 145 million per foot (6.6 to 475.7 million per meter) (Figure 2). The test section is approximately 8.2 feet (2.5 meter) by 8.2 feet (2.5 meter) and 25 feet (7.6 meter) long with a cross sectional area of 67.2 ft^2 (6.2 m^2). The test section has six slots in the ceiling, six slots in the floor, 14 re-entry flaps in the top and bottom walls to prevent the flow from choking the tunnel at near-sonic conditions, and a 6% openness ratio based on the wall surface area (wall divergence set at zero). See Reference 2. NTF can be operated using either air or nitrogen as the test medium. During air operations temperature is controlled by a water-fed heat exchanger located in the settling chamber. During nitrogen operations the temperature is controlled by evaporating liquid nitrogen which is dispersed into the tunnel circuit just upstream of the fan through 296 nozzles in 12 bundles at a maximum rate 1,100 lbs/sec (164 gallons/sec; 36K liters/sec). 430 tons of LN2 are produced on site per day and stored in two tanks with a total capacity of 3,800 tons (1,150M gallons; 4.4M liters). These two modes provide the ability to operate the tunnel between -250°F (-157°C) and +150°F (+65°C). Thermal insulation that resides inside the pressure shell minimizes energy consumption. Pressure is controlled by two large vent valves connected to the tunnel circuit between turns #3 and #4. The facility can operate from 14.7 psia (101.4KPa) to 133 psia (917.0 KPa) (1 to 9 atmospheres; 1.01 to 9.2 bar) in either medium. The tunnel drive system is powered by a variable speed motor that has adjusteable maximum torque or power output that peaks at 360 RPM. At 360 RPM the maximum power is 135,000 Hp (101 MW) and that maximum power level is maintained up to 600 RPM. The compressor consists of a fixed pitch, single stage, 25-bladed, 20-foot (6.1m) fan with variable inlet guide vanes. For fine Mach number control, the inlet guide vanes are varied to achieve the required compression ratio to maintain the desired Mach number. Temperature can

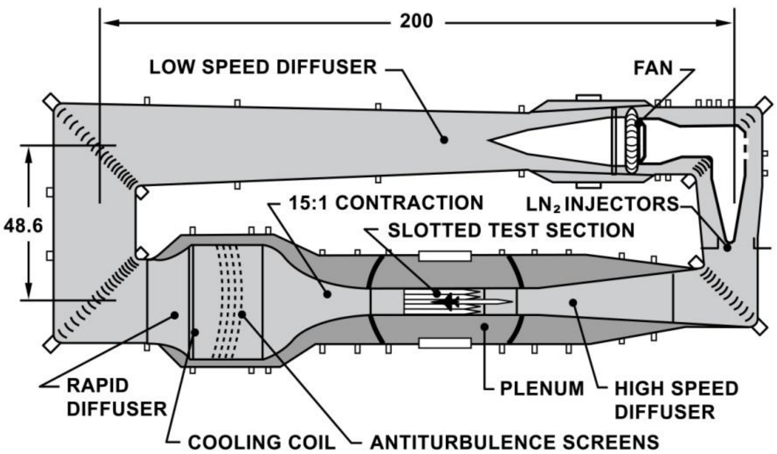


Figure 1. NTF Circuit Schematic

be maintained within ± 0.3°F (0.17°C) for N2 operations or ± 1°F (0.56°C) for air operations; Pressure ± 0.07 psi (482 Pa); Mach number ± 0.001 or better.

The NTF supports testing of stability and control, cruise performance, stall buffet onset, and configuration aerodynamics. The full-span model support system is a circular arc sector that provides an angle-of-attack range of -11.5° to 19.0° at a rate of up to 4° per second. The strut incorporates a roll drive with a range of ±180° which, in conjunction with the pitch of the strut, is able to provide pitch and yaw data. The normal force load capacity of the strut is 27,000 lbs (120,102 N). Several sting and strut combinations are available for testing of aerodynamic models. The NTF can accommodate various types of internal 6-component strain gage balances. Onboard angle-of-attack accelerometers are available that include thermal conditioning systems for cryogenic operation.

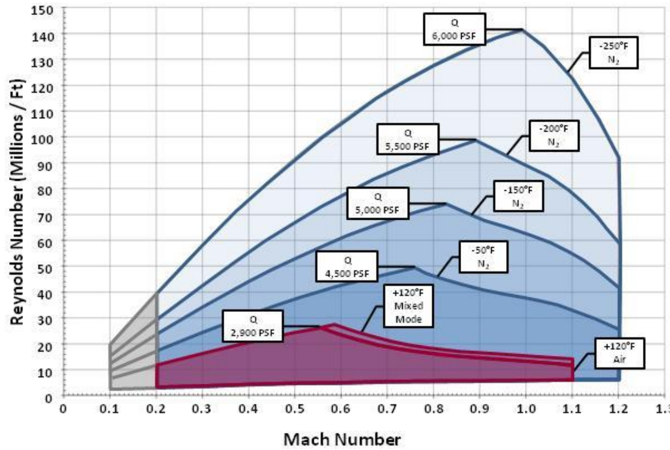


Figure 2. NTF Operating Map

The NTF can also conduct semi-span model investigations using the Sidewall Model Support System (SMSS). The SMSS is installed in the test section wall with the model mounted on the test section horizontal centerline. The SMSS has a ± 35° pitch capability and can accommodate external 5-component strain gage balances up to 27,000 lbs (120,102 N) of normal force. The model is attached via adaptive hardware to the balance, which is installed behind the test section wall within an insulated and heated enclosure. The SMSS can also accommodate a dual channel, high pressure air system to support propulsion airframe integration studies, circulation control high-lift concepts, powered lift, and cruise separation flow control.

A. Fan Loading

The compressor consists of a fixed pitch, single stage, 25- bladed fan with 24 Variable Inlet Guide vanes (IGV). See Figure 3. The fan pressure ratio or the fan loading "F" can be varied either by varying the motor rpm or flow deflection of the absolute flow through the rotor and is given by:

$$\mathbf{F = \rho\, U\, (C\theta_2 - C\theta_1)}$$

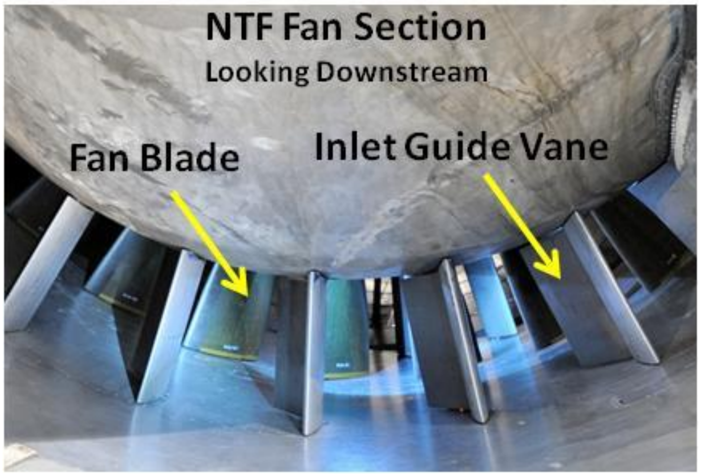


Figure 3. NTF Fan Section

Where the blade speed $U = \pi DN/60$ ft/s and ($C\theta_2 - C\theta_1$) is the absolute flow angle deflection through the rotor. The flow angle deflection is varied by moving the IGV trailing edges which have a turning range of +30° to -30°, δ°, corresponding to unloaded to fully loaded (low Mach number to high Mach number) conditions, respectively. The loading process is illustrated through the following 2-D flow velocity vector diagram (Figure 4).

B. The NTF IGV System Description

The IGV are mounted on a steel ring and are connected to a linkage mechanism. The circular motion of the ring, imparted by two hydraulic actuators located within the nacelle (Figure 5) drives all the 24 trailing edges together in unison. An electro-hydraulic 28-gpm (106-lpm) servo valve working at 2000 psig (137.9 bar), drives the twin actuators. The high-pressure hydraulic lines are carried from outside the NTF shell through the nacelle. The nacelle has large volume space and it experiences the tunnel temperature environment. Servo hydraulic systems do not have any flow except when the actuators move. Thus the oil slug from servo valve to actuator cylinder is predominantly stationary. Initially, hydraulic fluid in this 50 foot (15.24m) long high pressure line from servo to actuator would cool under cryogenic conditions making IGV control difficult. Hence a low-pressure purge line was added to jacket and warm the high-pressure lines. This low-pressure line circulates heated oil to maintain a desired temperature of about 100°F (37.8°C). This warm jacket keeps the stationary high-pressure oil line warm and the IGV controls work well even after prolonged operations in cryogenic conditions.

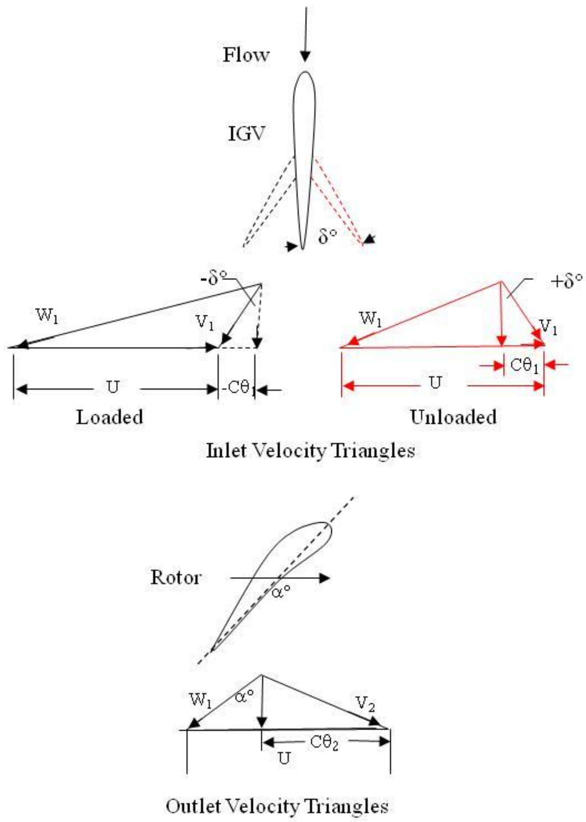


Figure 4. Flow Velocity Triangles Showing Fan Loading Process

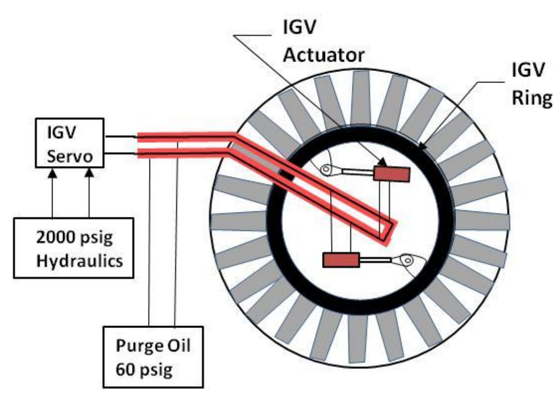


Figure 5. The IGV Actuator Mechanism

The IGV ring is a center-less component that is supported by the top two rollers and guided by them and two additional lower rollers that enables its rotation concentric with the drive shaft. These rollers are mounted on a rigid transfer case, as shown in Figure 6. The IGV ring hangs vertically from the

top two rollers having a small clearance of 0.025 inches (0.635 mm) from the bottom rollers. During cryogenic operations, a large temperature gradient between the IGV ring and the transfer case results in shrinking of the ring relative to the transfer case. This causes ring-roller interference as shown in Figure 6, and induces undesirable loads on the rollers. Therefore, the operation of the IGV must ensure safe load conditions doing so by utilizing various interlocks to provide an acceptable temperature gradient between IGV ring and the transfer case.

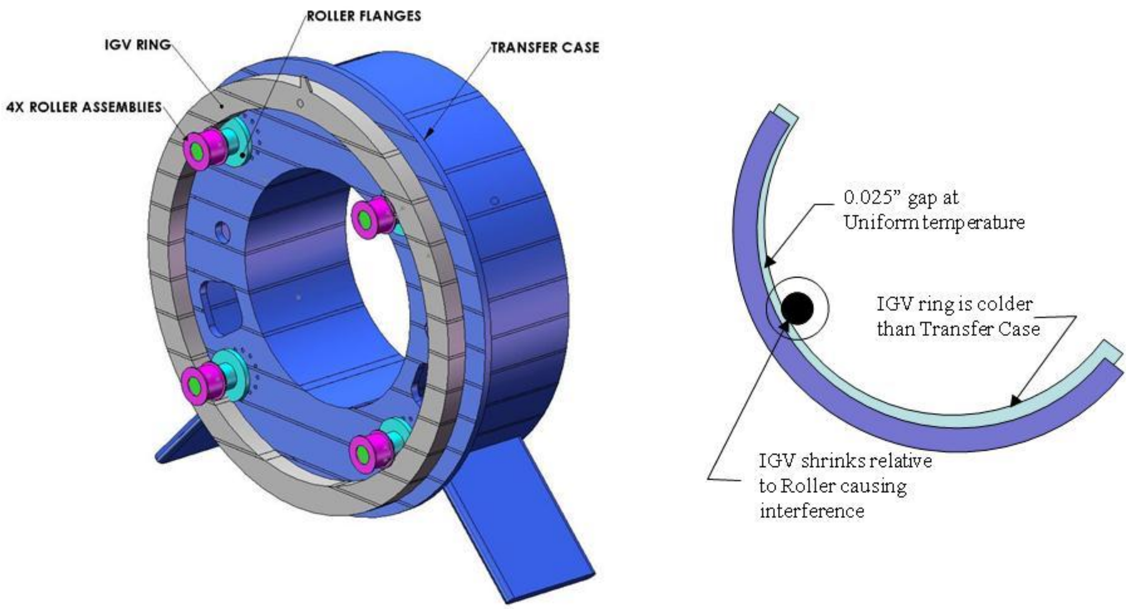


Figure 6. IGV Ring-Roller Interference at Cold Conditions

C. Safety Limits for Fan and IGV Operations based on ΔT

Based on a simple finite-difference thermal analysis and stress calculations from the 1980's, two levels of safety limits have been incorporated in the Facility Automation System's (FAS) Programmable Logical Controls (PLC) that prohibits the operation of IGV actuator mechanism for $\Delta T > 35^oF$ (19.4°C) and fan operation for $\Delta T > 40^oF$ (22.2°C), The average transfer case temperature is defined to be $(T_1+T_2+T_3+T_4)/4$, while the average IGV ring temperature is defined to be $(T_5+T_6+T_7)/3$ (See Figure 7). The maximum difference between these two average temperatures is defined as ΔT.

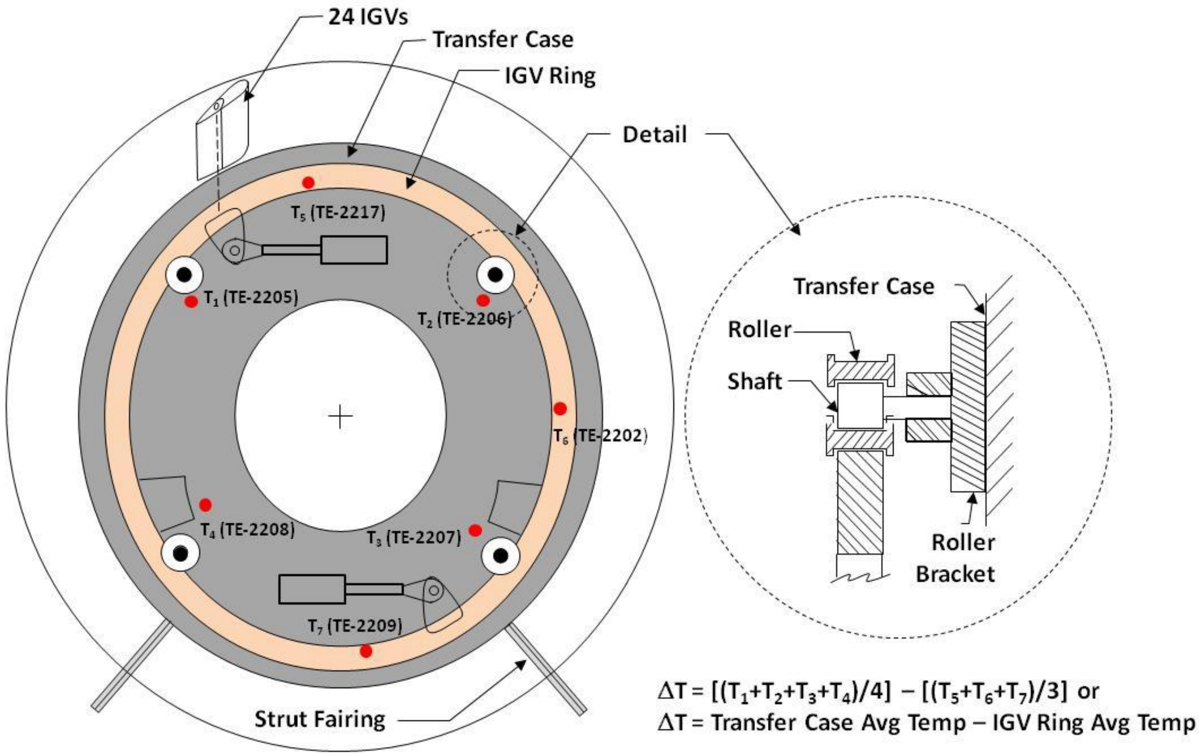


Figure 7. Temperature Measurement Locations on the IGV Ring and Transfer Case

D. Historical Test Data on ΔT

The measured temperature history from different locations of the IGV ring and transfer case is shown in Figure 8. It is clear that the bottom portion of the structure became colder with time. In particular, the bottom region of the IGV ring experienced much colder temperatures compared to other locations, as indicated by the thermo couple TE 2209.

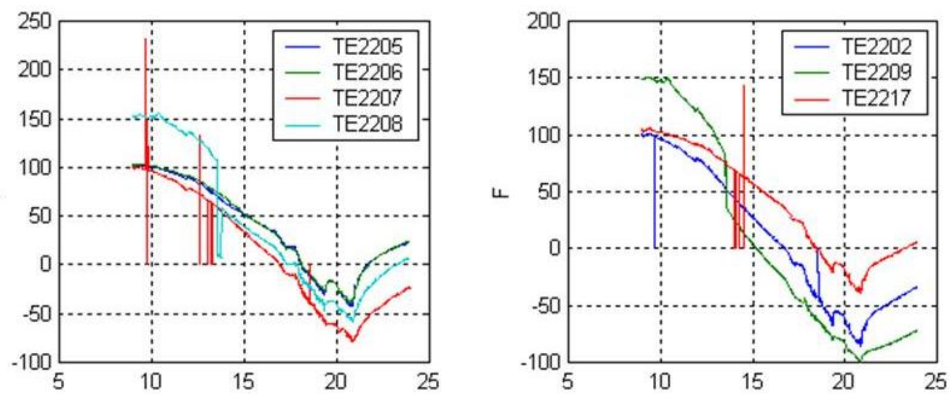
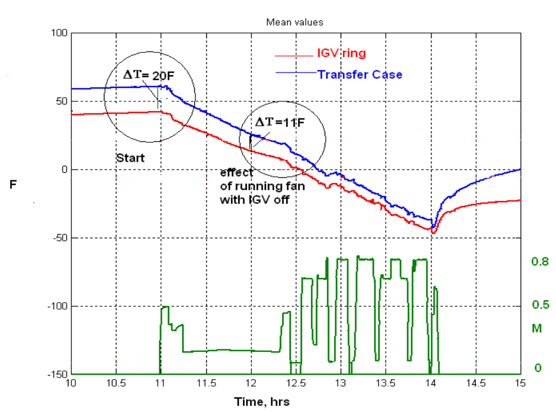


Figure 8. Temperature Data from IGV Assembly; 2007 Test

Figure 9 shows ΔT variation with time, calculated from the data of Figure 8 using the definition for ΔT given in Section C, for two different cryogenic tests conducted in 2005 and 2007. In one

case, the ΔT was decreasing with time and in the other case it was increasing. However, in both cases, the ΔT stayed well within the IGV operational permissible safety limit of 35°F (19.4°C) allowing data acquisition. Some other times (data not shown), during data acquisition the ΔT increased beyond the allowable safety limit and tripped the drive motor protection system. Various measures have been initiated in the past to address the ΔT problem. An electrically heated hot air circulation system is used in the IGV region. By procedure, during cool-down for cryogenic operations, all tunnel heaters are started when the tunnel temp reaches 50°F (10°C). This prevents the systems/structure from cold soaking. On warm up the heaters are turned off when the average plenum structure temp reaches -20°F (-28.9°C) and none are below -40°F (-40°C). In addition, insulation around IGV structure was reinforced and several tactical methods have been employed for tunnel conditioning to contain ΔT growth. These efforts did not produce consistent success. The hot air circulation was not providing an effective convective heat transfer across the IGV structure to maintain its temperature uniformity and contain ΔT. This is due to restricted space around the structure within the nacelle, heat addition to the transfer case from the bearings oil feed and return pipelines that are routed through the transfer case, and thermal buoyancy effects.

However, the ΔT diverges when the structure was allowed to warm up naturally to reach operable conditions after the fan was stopped either for a model change or at the end of the second shift operation. It can be seen from Figure 8 that from the time the fan was stopped at14:00 hrs and 21:00 hrs, during two different tests, the ΔT grew. In one case, (2007 test), ΔT increased to 41°F (22.8°C) and beyond and took several hours before returning to within th allowable limits and allowing for the tests to continue. When the tunnel fan is switched off, while IGV structure is at cryogenic conditions, the massive (12,000 lbs/5,443 KG) IGV ring warms up at a slower rate due to its higher thermal inertia compared to the transfer case and the minimum conduction heat transfer path available for the ring through the line contact available at the rollers.



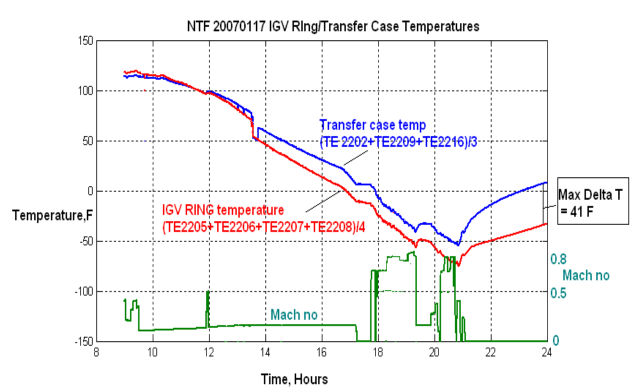


Figure 9. Historical ΔT Data During 2005 and 2007 Tests

E. The CAD-FEA Analysis

The thermal analysis of the ring-roller assembly that was conducted in the 1980's has been recently revisited, using SolidWorks[TM]-Cosmos CAD modeling and Finite Element Analysis (FEA) (Ref. 3). The CAD-FEA analysis used the above measured temperature data set shown in Figure 7 and computed the linear and non-linear solutions of the temperature distribution from top to bottom of the IGV structure shown in Figure 10. The analysis assumed only vertical temperature gradients due to buoyancy and neglected lateral gradients and the temperature distribution. The IGV ring is always colder compared to the transfer case.

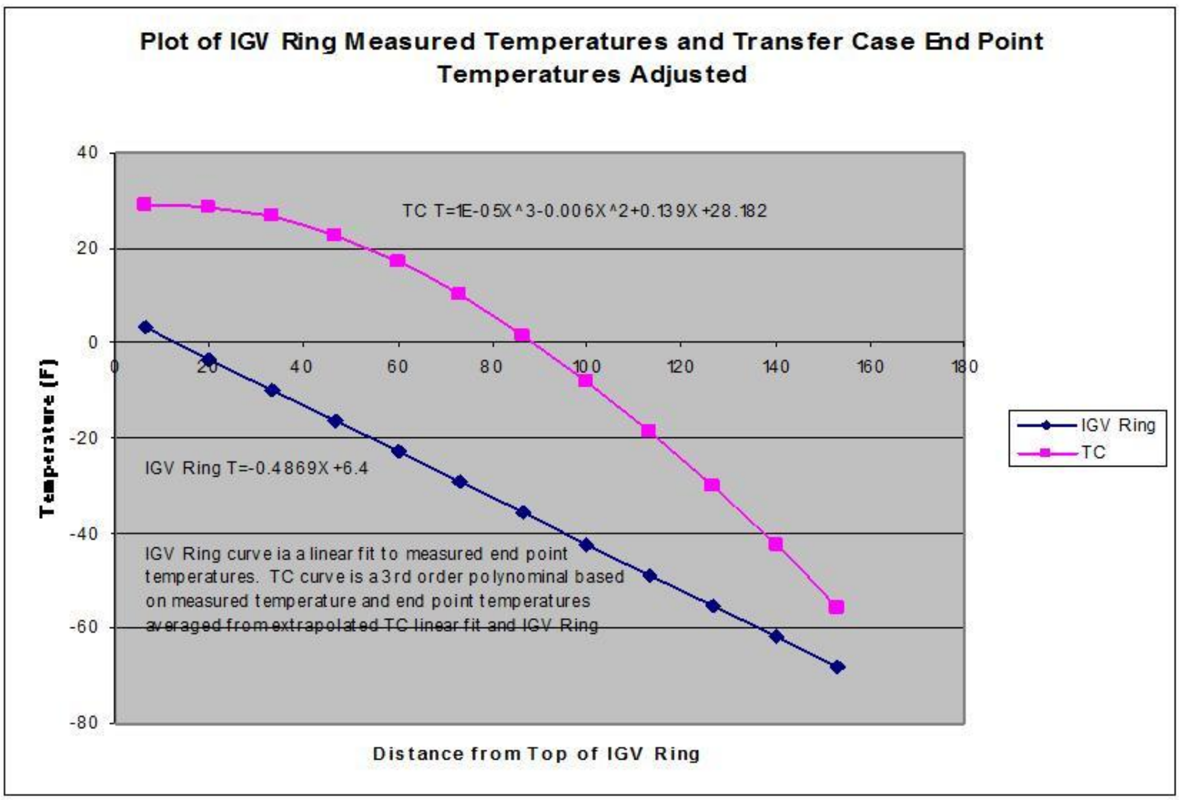


Figure 10. Temperature Distribution on the IGV Ring

The ring-roller interference and associated loads on the roller for various ΔT is shown in Figure 11. In the case of linear analysis, which is the worst case scenario, the ring-roller interference begins at about ΔT = 39^{o}F (21.7°C). At ΔT = 44^{o}F (24.4°C), the linear analysis, shows an interference of 0.004 inches (0.102 mm) between the IGV ring and bottom of the rollers. For this interference the calculated ring loading was 16,000 lbs (71,172 N) (Ref. 3). However, the results

from nonlinear analysis shows no ring-roller interference up about ΔT = 50°F (27.7°C) and suggests that the thermal analysis from the 1980's that limited the IGV operation to a ΔT = 35°F (19.4°C) is conservative.

Based on the FEA, the following options were considered: 1. tactically control ΔT by operating only the fan at ΔT<= 44°F (24.4°C) and cool the transfer case, 2. heat the IGV ring alone, and 3. permit higher ΔT limits for fan operation. During a cryogenic test in January 2012, when the tunnel temperature was -220°F (-140.0°C), the ΔT exceeded the fan operational PLC limit and reached about 42°F (5.6°C). At that time, the ΔT limit was relaxed to 45°F (23.3°C) and the fan was operated as suggested by option 1. The ΔT started decreasing initially, but the moment the next test condition of -250°F (-156.7°C) was set in the controls, the tunnel started cooling down further resulting in the ΔT increase. As discussed in Section D, the tactical management of ΔT was not always successful due to the complex nature of heat transfer in the IGV area. It was decided to heat the IGV ring locally during the next cryogenic test and explore option 2.

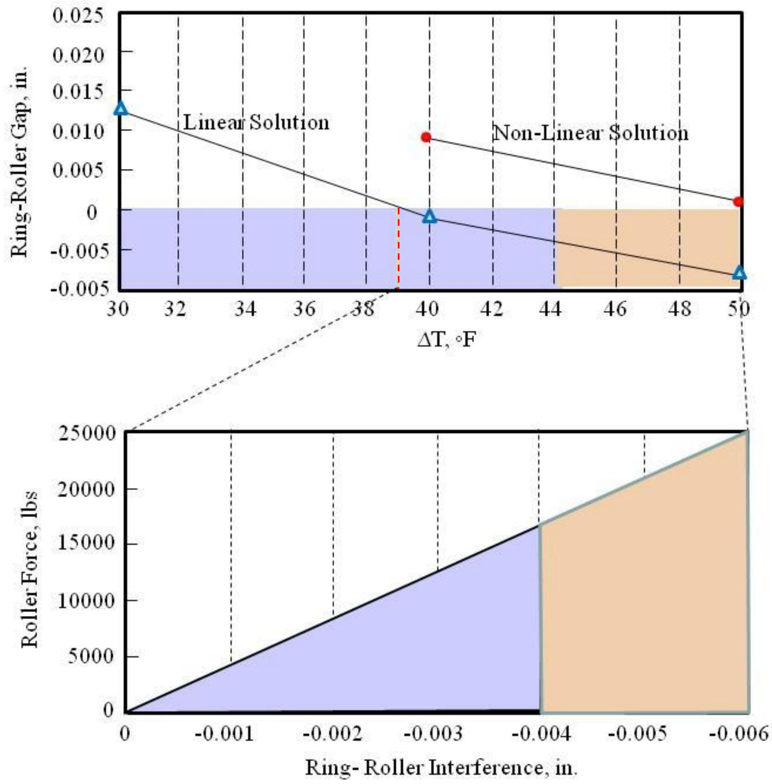


Figure 11. The IGV Ring-Roller Interference Load caused by ΔT

F. *Mitigation of* ΔT problem During Test 211, 2012

During cryogenic test 211 performed in January, 2012, the operation, ΔT increased beyond the limits normally allowed for IGV operation. A schematic representation of tunnel free-stream, deep structure, and ΔT temperature variations are shown in Figure 12.

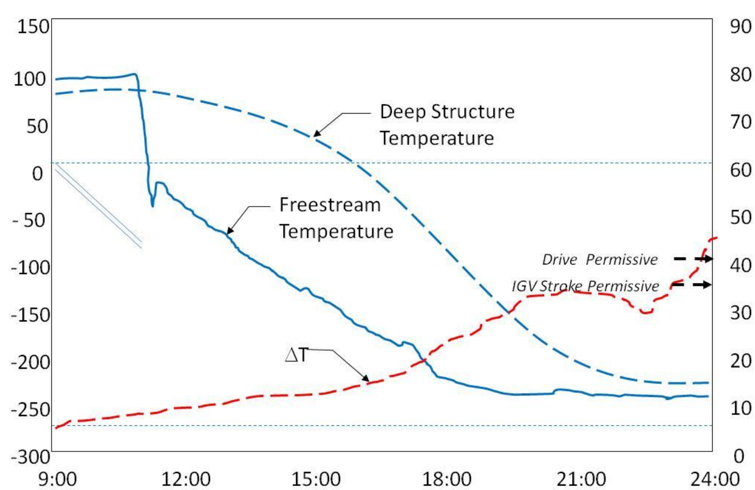


Figure 12. Tunnel free-stream, deep structure, and ΔT Variation

During Test 211, the tunnel cool down started around 11:00 hrs and the tunnel conditioning was completed at about 23:00 hrs. At that time, the free-stream and deep structure temperatures were within 5^{o}F (2.8°C) of each other. The test crew prepared to conduct pitch polar sweeps but ΔT started diverging and reached the IGV stroke limit interrupting the test operations.

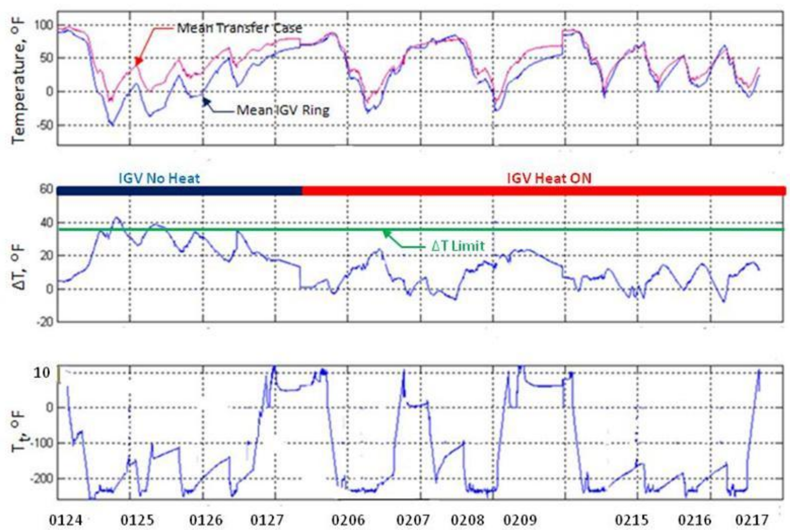


Figure 13. The ΔT Variation Without and With Heat Addition

Figure 13 shows the historical IGV Ring and Transfer Case mean temperature data along with the tunnel free-stream temperature and ΔT variations for the entire Test 211 which spanned a period from January 24th to February 17th of 2012. It can be seen from Figure 13 that subsequent to the tunnel cool down process during the second shift on January 24th, the ΔT reached approximately 42^{o}F (23.3°C) preventing tunnel operations. An exploded view of this event is shown in the previous Figure 12. On four separate occasions, tunnel operations were interrupted due to ΔT problem from January 24th to January 27th resulting in several hours of down time and unnecessary LN_2 loss usage. On January 27th, upon interruption, the tunnel was warmed up to the ambient temperature and a new solution to this problem was tried. Heating pads were mounted on to the IGV ring as described below.

Several electrical heating pads of varying size and power were mounted at the bottom of the IGV ring on three separate surfaces providing coverage from the 4-o'clock to 8-o'clock region. A total number of nineteen (19) heating pads were mounted on the ring: eight (8) pads each having dimensions of 10 in. x 6 in. (25.4 cm x 15.2 cm) and 300 Watts power output, eight (8) pads each having dimensions of 5 in. x 2 in. (12.7 cm x 5.1 cm) and 50 Watts power output, and three (3) pads each having dimensions of 15 in. x 6 in. (38.1 cm x 15.2 cm) and 450 Watts power output to provide a total power of 4.15 KW. The photographs in Figure 14 show the locations of thermocouples placed near the heating pads that were mounted on the inner face of the ring. Thermocouple TE 2209 (Photograph on the left) thermocouple TE 2202 (Photograph on the right) were at a distance of about 6 and 28.5 inches (15.2 and 72.4 cm) away from the edge of the pads, respectively.

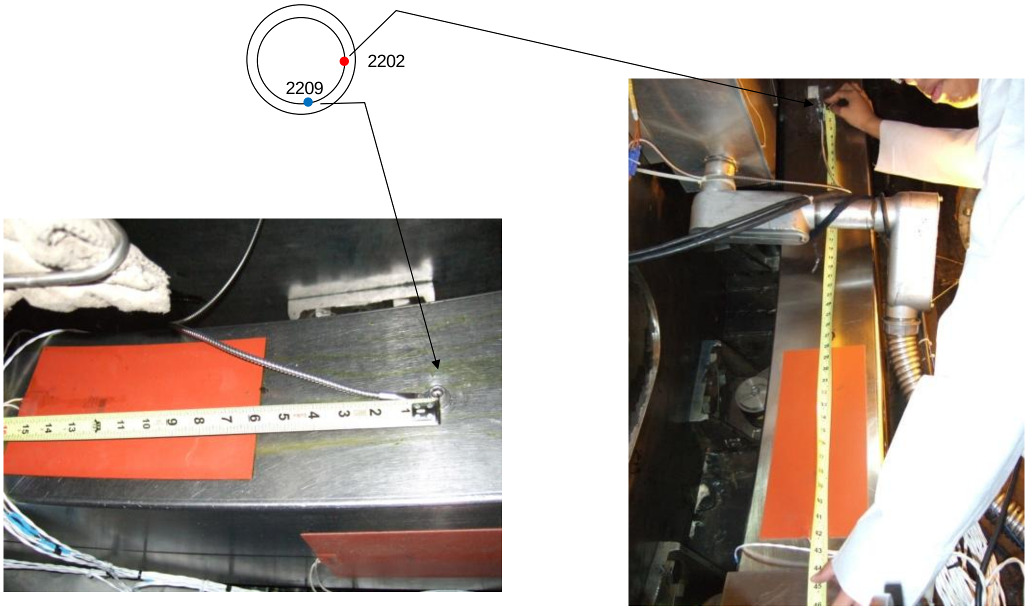


Figure 14. Photograph of the Thermocouples and Heating Pads Mounted on the IGV Ring

On February 6th the test was restarted with the new heating pads warming the IGV ring at the start of the cool down process. The small amount of heat addition to the IGV ring (~4 KW), for a long duration (~12 Hrs), from the start of the tunnel cool down process to the final conditioned state of the tunnel, kept the ΔT growth under check, within the limits of about 22°F (12.2°C) (Figure 13). Based on historical data the productivity loss prior to using the heating pads was estimated at $300K/year. The analysis, material and labor costs for the heating pad modifications were approximately $6,000, showing a great return on investment. The IGV heating circuit has been integrated with other heating systems of the tunnel and it is now automatically activated during cryogenic operation.

G. Conclusions

A long standing productivity issue has been resolved at the NTF. The NTF Fan Inlet Guide Vanes (IGV) assembly is used to control Mach number. During cryogenic operations at high Reynolds Numbers, the IGV can experience large thermal gradients resulting in high and unsafe thermal stresses in the structure. In recent years, deterioration of NTF insulation has resulted in the IGV thermal gradient exceeding the safe ΔT limit of 35°F (19.4°C)) very frequently during cryogenic operations, particularly during model access. Once the ΔT exceeds the safe limit, the tunnel cannot be operated. The natural warm-up required for ΔT recovery takes days causing considerable productivity loss at NTF. Based on historical data this productivity loss is estimated at $300K/year. An IGV ring heating system (at a cost of $6K) was incorporated to address this issue and the system performance was successfully demonstrated during the Test 211 and subsequent cryogenic tests.

H. References

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